MONTHLY WEATHER REVIEW

Editor, EDGAR W. WOOLARD

VOL. 70, No. 1
W. B. No. 1348

JANUARY 1942

CLOSED MAR. 3, 1942
ISSUED 1942

ON A HYPOTHESIS CONCERNING THE NORMAL DEVELOPMENT AND DISINTEGRATION OF TROPICAL HURRICANES*

By W. F. McDONALD

[U. S. Weather Bureau, Washington, D. C., Nov. 1941]

Facts of observation on the origin of tropical cyclones are quite meager, although increasing at a steady rate. These storms begin most commonly in marine tropical regions, remote from areas covered by a network of meteorological land stations. Ships' observations are inadequate to give more than inconclusive hints as to the physical processes that attend the origin and development of the hurricane. The data from fully-developed hurricanes are much more complete, because mature storms often travel into regions where observations from ships and shore stations are numerous. Much still remains to be learned regarding the mechanism of mature cyclones, whether of tropical or extratropical origin, especially regarding the processes that are particularly important in forecasting; but origins are even more obscure.

In attempting to utilize the relatively meager body of knowledge regarding the inception and development of tropical cyclones, it may be helpful to formulate tentative working hypotheses, and examine to what extent they serve to connect the observations into logical relationship, with a minimum of exceptions. The present paper is an effort of this kind.

Let us first review some of the commonly accepted facts regarding normal tropical cyclones:

1. Tropical cyclones usually develop in regions where large masses of relatively homogeneous tropical marine air are normally in steady motion, as trade or monsoon winds.
2. The inception of a tropical cyclone is commonly associated with some conflict or disturbance in the normal wind stream of the locality.
3. The diameter of tropical cyclones is usually less at the beginning than at later stages of development.
4. The weight of available evidence indicates that as long as the cyclone remains within the Tropics and does not encounter a marked discontinuity, the barometric minimum for the particular storm does not deepen materially after 2 or 3 days from the time when true vortical character has been established. In other words, the normal increase in diameter of the cyclone with passage of time is usually not attended by a corresponding increase in depth of barometric minimum.
5. Tropical cyclones seldom, if ever, decrease in diameter with passage of time, once the vortex is established, and this is true even of the rare storm that moves from higher to lower latitudes.
6. Tropical disturbances usually decrease in intensity and disappear by rise of barometer at the center, without material contraction in the diameters of the closed isobars.

These several statements will fall into logical connection if there is a cycle of development, growth, and degeneration of the kind to be described in the remainder of this paper; the assumption is made that the normal life history of the cyclone is free from encounter with bold topographic barriers or heterogeneous air masses.

Given relatively uniform thermodynamic and kinematic characteristics over a large-scale atmospheric region in which a hurricane develops and travels, it would seem logical to expect such general factors to fix a limit to the intensity of the disturbance, once it is started.

Such conditions do, in general, characterize the regions from latitude 30° N. to 30° S., in which tropical cyclones most generally originate and maintain their distinctive character. It is hardly open to question that there is an extreme limit to the intensity of the hurricane-type storm; no central barometer reading lower than 26 inches has yet been recorded in a tropical cyclone. The variation from storm to storm above this limit is wide but there is considerable evidence pointing to the probability that the barometric intensity of any given disturbance has become established within a few days after the vortex originates.

Millas [1] concludes that the whole period of vortical development in West Indian hurricanes, from first causative action to full intensity, is of the order of about 8 days on the average. In a short note on a group of low barometer readings reported in 1933 from ships involved in West Indian disturbances, the present writer made the following remark:[2]

> The five readings below 28 inches were obtained in four separate storms. Furthermore, the lowest reading in each of these storms was observed within 1 or 2 days after the time at which the disturbance was definitely located in our reports, and no lower readings thereafter have as yet come to light, although in all cases these storms appear to have increased in extent and destructive power as they passed onward to later stages of development. This group of records therefore supports the view that tropical disturbances, often, or perhaps commonly, arise as intense vortices of small diameter, which expand in area and decrease in intensity as they progress.

The record minimum barometer actually observed in a cyclonic vortex at sea level was on the Dutch S. S. *Sapoeraea*, at the center of a typhoon in the Pacific about 460 miles east of Luzon.[3] This reading, 26.185 inches, was taken at a location so situated with reference to the region of most common origin of typhoons, as to lend support to the assumption that in this case also the storm may very probably have been only a few days old at the time of the observation.

A new record was established for the minimum barometer reading observed at sea level in the Western Hemisphere, when, after careful investigation, the Weather Bureau accepted a pressure of 26.35 inches as the official

*Modification of a paper presented before the American Meteorological Society, Miami, Fla., May 9, 1941.

[1] J. C. Millas. Genesis of Hurricanes of the Western Caribbean Sea. Reported in *Bulletin A. M. S.*, vol. 22, p. 78.

[2] McDonald, W. F. Low Barometer Readings in West Indian Disturbances of 1932 and 1933. MONTHLY WEATHER REVIEW, vol. 61, p. 273.

[3] *Meteorological Magazine* (London), February, 1933, p. 18, quoting *Nature*, (London) issue of August 18, 1928, p. 251.

record in the Florida Keys storm of September 2, 1935.[4] This unusual pressure minimum and its attendant intense hurricane winds occurred within a storm diameter of about 50 miles, not more than 3 days after the initial cyclonic development near Turks Island. Data on this storm indicate that the vortex was constantly deepening during those 3 days. Pressure at the center began to rise as the disturbance passed beyond the Florida Keys; at the same time, the diameter of the area of hurricane winds increased. All of these developments took place during a period in which the cyclone moved over water surfaces broken only by small island areas; and the changes in the storm seem to have resulted from the progressive operation of causes inherent in the mechanism of the cyclone, rather than from any external influence.

The American S. S. *Virginia*, on September 20, 1933, passed through the center of a hurricane in the western Caribbean. The existence of this storm had not previously been recognized although an incipient condition had been noted during the 4 days preceding. This ship experienced a barometer of 27.44 inches, with a pressure fall of more than 2 inches within an hour and a half after entering the storm. It is estimated that this vortex was not more than 40 miles across at the time but was increasing rapidly in diameter.

The tropical hurricanes that have occasionally formed in the Gulf of Mexico and moved northward, to pass within 2 or 3 days across the middle Gulf Coast, have usually been of small diameter, with extraordinary violence near the center. Vortices that have crossed Puerto Rico have more often than not been of similar character, and examination of our charts of hurricane tracks will show that the region of origin of many of these Puerto Rican storms is not far east of the island.

From such evidence it seems logical to suppose that the preexisting thermodynamic state of the tropical air mass provides an environment in which intense local activity may occur, but *which at the same time predetermines a limit of intensity beyond which the action cannot go.*

Atmospheric soundings reported from several places in the Tropics afford some interesting evidence on this point. The radiosonde records from Swan Island in August 1940, show a more or less constant presence of a deep air mass in which the lapse rate equalled or exceeded the moist adiabatic up to 7,000 meters and on some days very much beyond that level. Moisture content was quite high, hence tremendous amounts of energy were potentially available in a state of conditional instability. One or more barrier layers, with lapse rate somewhat less than the moist adiabatic, existed in each case, but these barriers were slight and could undoubtedly be broken by any unusually strong convectional impulse from the very moist surface air layer.

A single daily temperature curve (for Sept. 10, 1940) from Swan Island, and the *monthly* average lapse curves for August 1940, at Swan Island, and for September 1940, at St. Thomas, V. I., are shown on figure 1.

The St. Thomas record is included because it shows a very steep lapse (almost superadiabatic) in the average for the lowest 500 meters. The depth of this unusual layer varied from 230 to 944 meters in 25 out of 28 daily sounding records available for September 1940. This wide variability, and the character of the changes in depth of the superadiabatic layer from day to day (which showed a peculiar persistence or trend over several days) are evidence against one explanation that has been offered for this remarkable steepness of lapse rate near the surface, namely, that it is a combination of effects from strong surface heating of the airfield and of instrumental heating while the airplane was being made ready for the sounding flight. Further evidence for the actual common existence of an excessively steep lapse rate near the surface in the trade wind belt of the North Atlantic, comes from the records[5] of the *Meteor* expedition in 1927, examples of which are shown in figure 2. These soundings were made from the deck of a ship, and there could have been no land surface effect because the locations were hundreds of miles from shore, in the eastern part of the tropical North Atlantic and in the steady trade wind belt.

The problem of how such steep lapse rates can commonly exist in air heavily charged with moisture has not been completely solved.[6] The observations cited above are from the trade-wind belt, where there is the fullest development of a large-scale steady state of the general wind stream in a relatively stable barometric field, and vorticity is at a minimum. Perhaps in such a field, the character of the wind stream at lower levels introduces what may be termed a factor of "kinematic or dynamic stability," which tends to suppress small perturbations of convectional nature so long as the broadscale flow pattern is maintained in a generally steady state; e. g., Brooks has remarked, concerning the island regions of the West Indies[7] "In midsummer, however, growth of the Bermuda-Azores HIGH, making stronger trades that tear convectional columns apart before they produce much rain, causes a distinct break in the warm season rainy period." Holzer, of the University of New Mexico, has reported similarly on the suppression of anticipated thunderstorm activity observed by him near Albuquerque when there was marked shear between the upper and lower strata involved in cumulus formations.

Any dynamic factor tending to counteract instability in trade wind or monsoon regions would weaken or disappear if the general wind stream should be appropriately disturbed, in which case the instability of the lowest layer might more readily lead to convectional overturning. Such overturning would tend to appear as local shower and squall conditions over the general area in which dynamic stability was weakened. Showers and squalls mark the "*preliminary*" phase of tropical cyclone origin.

Tropical storms usually begin as mild, but characteristically cyclonic, manifestations over an extensive area of warm ocean surface, several hundred miles in diameter. The normal course of the winds and weather suffers definite interruption; pressure falls slightly throughout the whole region of disturbance; the general drift of easterly winds is broken down, so that winds of southerly or even of westerly components appear; and numerous rain and thundersqualls are reported by ships that enter this region where the stage-setting for rapid cyclonic development is being slowly prepared.

The duration of the "*preliminary*" phase varies, but it commonly extends over several days, during which time there is likely to be a drift of the disturbed area in the direction in which the true vortex travels after it finally appears and moves away from the region of formation.

At the beginning there is neither a closed isobar as much as one-tenth of an inch below the surrounding field of

[4] McDonald, W. F. The hurricane of August 31 to September 6, 1935. Also lowest barometer reading in the Florida Keys storm of September 2, 1935. MONTHLY WEATHER REVIEW, 1935, 63:269–271; 295.

[5] Kuhlbrodt and Reger: Beilagen zu das Aerologische Beobachtungs-material. *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition "Meteor" 1925–27.* Berlin and Leipzig 1933.

[6] See, e. g., Sverre Petterssen: *Weather Analysis and Forecasting* (New York, 1940), p. 79.

[7] C. F. Brooks. Some North American connections of Caribbean climate. Reported in *Bulletin American Meteoroological Society*, vol. 22, p. 79, 1941.

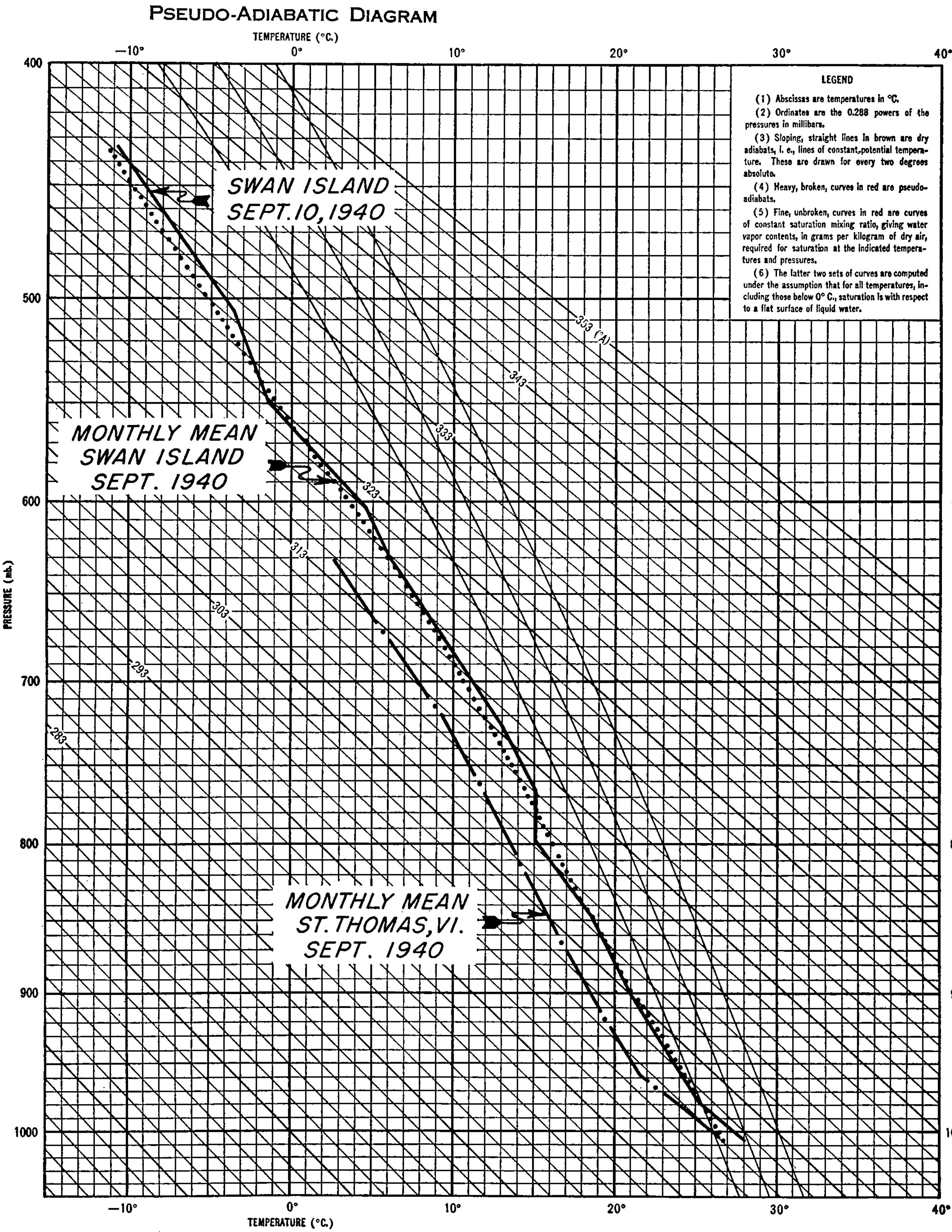

FIGURE 1.—Temperature lapse curves for Swan Island and St. Thomas, V. I., September 1940. Plotted with pseudo-adiabatic diagram.

pressure, nor is there necessarily any increase of preexistent wind forces. The slight lowering of pressure at the outset forms but a bend in the broad sweep of almost parallel isobars on the equatorial side of the semipermanent oceanic anticyclone. The altered trend of isobars is of course attended by changes of wind direction, as already noted; but usually those winds that are turned away from their previous inclination toward the Equator are at first diminished in force. It is only in the quarter where the altered direction of isobars continues closely to correspond with the preexistent general wind stream that wind force is maintained, or perhaps strengthened, in this very early stage of incipient disturbance.

As the pressure continues its slight downward course, the bend may loop into a closed isobar, and winds from southerly directions thereafter increase in force. When this happens, the preliminary phase of development is about to end, and the second stage to begin. What produces a concentration of energy into the true beginnings of a definite cyclone in some cases, and prevents it in others that appear equally favorable, is a problem for further investigation.

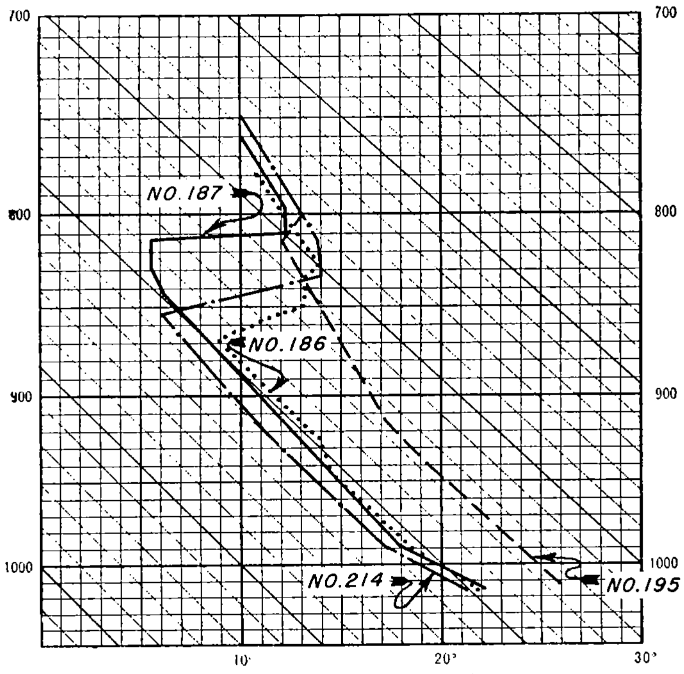

FIGURE 2.—Temperature lapse curves for stations in tropical North Atlantic, eastern portion; from reports of survey ship *Meteor*, as follows: No. 186; March 20, 1927. No. 187; March 21, 1927. No. 195; March 31, 1927. No. 214; May 8, 1927.

The squally local disturbances producing heavy rain, and the small general fall in pressure, may be assumed to be physically interrelated phenomena. The rains occur as a result of convectional overturning. The pressure fall may possibly be a primary result of loss of atmospheric mass in these rains, since one effect of heavy general precipitation over a relatively large region, where there is no ready compensation by inflow, is to produce a slight decrease in pressure amounting to about 2 mb. for each inch of rainfall.

Large-scale convectional perturbation may therefore attend a disturbance of the normal balance of wind and barometer in the trade wind stream, and lead to a release from what is here called the factor of dynamic stability. This causative action may appear as a progressive wave disturbance traveling westward through the trades; and the rain area and attendant fall in pressure would then accompany the disturbing wave. Dunn [8] has discussed this type of occurrence in relation to tropical cyclogenesis; and Deppermann [9] has placed great stress on disturbances to normal trade and monsoon streams as probable originating causes of typhoons.

An important source of disturbance in the West Indies region is the southward bulge of isobars following impact of a southeastward-moving summer anticyclone from the United States. W. R. Stevens, an experienced hurricane forecaster, has repeatedly remarked that he always goes on the alert when, in the hurricane season, such a movement occurs. The action takes place in summer because a continental anticyclone can then be a deep formation at a relatively high temperature, so that at least a part of its mass may be in condition to undergo assimilation into the tropical marine high-pressure area on advancing over the continental border onto the North Atlantic. The added mass produces a distortion of the marine anticyclone, appearing in the tropics as a local bulge toward lower latitudes with a decided effect on the normal course of the trade wind stream in the area affected.

Such a bulge may remain more or less stationary over several days. If localized heavy rains thus continue for several days in the same general region, the cumulative effect on pressure may be increased sufficiently to produce a definite convergence of air motion. Such may be the beginning of cyclonic action, which at low latitudes could thus concentrate and localize the released instability that would otherwise remain scattered and more or less self-limiting within the thermodynamic barriers that usually exist at several levels, as indicated in figure 1.

A vortex might thus develop and deepen if the overturning action at lower level breaks through to involve great depths of the conditionally unstable tropical marine atmosphere. Such action would be aided if there had been brought into place, by high-level advection, an overlying dry air mass with a temperature lapse definitely steeper than the moist adiabatic (if not potentially colder than the air below), thus providing a definite increase in lapse rate from the humid to the dry mass, with a small inversion acting as a barrier to spontaneous motion. Any lift forcing the upper part of the moist column into the drier air above would immediately create an increasing convectional instability where before such lift both masses were relatively stable. Thus there would begin a strong exchange across the boundary between the moist and dry air masses at high levels. This action would greatly increase the likelihood that the whole lower mass might become involved in an up-surge forming a self-perpetuating mechanism for vortical growth and continuing release of energy in the great reservoir of moist, conditionally unstable lower air.

Recalling then (1) that the general trade wind organization and any attending factor of dynamic suppression of instability builds up in summer, and (2) that it is only in summer that a continental anticyclone can be of the deep warm type which might permit it to advance aloft over the permanent marine anticyclone, we have in these two factors a combination of circumstances that should produce maximum opportunity for large-scale disturbance within the areas of conditional instability where West Indian hurricanes commonly originate.

Advection aloft need not be restricted to that coming from the North American continent. There is no reason to exclude the probability that any continental rain area could supply such a high-level, dry, air mass. For West

[8] G. E. Dunn. Cyclogenesis in the tropical Atlantic. *Bulletin American Meteorological Society*, vol. 21, pp. 215–229. June 1940.
[9] C. E. Deppermann. *Typhoons and depressions originating to the near east of the Philippines.* Manila 1940.

Indian hurricane regions, the overflow of warmed, dried air from the Amazon Basin across the mountain barriers of the north coast of South America, or of dry and potentially cool air from equatorial Africa, may at times provide the high-level factor for hurricane development in the Caribbean or North Atlantic area.

Without an air mass at high level potentially capable of leading to a release of instability in the lower moist air column, it is difficult to see how the actions of normal heating, turbulence, and humidification, acting more or less constantly from below upward, could so occasionally and irregularly break into the violence of a tropical cyclone.

Many local disturbances occur, with typical rain squalls and slight decreases in pressure, that do not lead to any development of a cyclonic vortex. In such cases we may suppose either that an appropriate factor was absent in the upper-air levels, or that the barriers to surface convection did not break down sufficiently to involve the whole air column, including an advection mass above the normal trade layer.

Clearly there can be a wide range of variation in the setting within which a cyclonic vortex may originate. The depth of the unstable air drawn into action, and the character of the superior air, are possibly more variable than the thermodynamic characteristics of the lower layers. Any vortical action once initiated would, however, progressively intensify until the whole column became involved, and the intensity of the vortical action would thus be determined and limited by the preexistent environment.

The preparatory slow development of large scale conditional instability plus the more rapid advent of a disturbing airflow aloft sets the stage, so to speak, for the actual inception of a tropical cyclone, and these may be said to constitute the first phase of the storm cycle.

The second phase is then initiated with the beginning of vortical motion, and lasts until the vortex reaches maximum intensity, as measured by the extreme barometric depression developed. Certain characteristics can be said to mark quite definitely the entrance upon this second phase. It is certainly under way when a closed isobar 3 mb. below its tropical surroundings, and a wind force of Beaufort 8 or higher, are observed. Tingley[10] has studied this second or deepening phase of a tropical cyclone developing in the Western Caribbean Sea.

Whatever the physical explanation of the thermodynamic action concentrated near the young vortex, there must be a positive eviction of air mass from within the intensifying field of rotary motion; by no other process can the central pressure be so greatly reduced. It is self-evident that a smaller mass of air can be more quickly and readily disposed of than a larger quantity; in other words, less power is required for an eviction of air sufficient to effect the same proportionate reduction of pressure over a smaller than over a larger area. This reasoning favors the theory that relatively small diameter is a characteristic of a deepening vortex. Formation at latitudes having low values for the deflective influence of the earth's rotation minimizes at this stage the tendency to broaden the field of rotation.

The extreme limit of pressure decrease in an intensifying tropical cyclone under the most favorable circumstances appears from available data to be of the order of 135 mb. (4 inches) reduction below the general barometric field. Evidence on this point has been cited above.

The smallest of the fully deepened vortices of which we have records are probably no more than 30 miles in horizontal extent. Assuming the height of atmosphere involved at the incipient stage to be from 2 to 5 miles, the relative proportions of the rotating atmospheric mass at first included would be similar to those of a disk of heavy cardboard of the order of an inch in diameter. There is no evidence whatever to indicate that a tropical cyclone begins with a vortex of the type of a waterspout or tornado, wherein the vertical axis of rotation is much longer than the horizontal diameter; what is described herein as the relatively small "focus" of vortical action within the more extensive region of preliminary disturbance appears to be from the very outset a section of atmosphere much broader in the horizontal direction than it is deep. The cyclone is small only by comparison with the potentiality of later growth, that under favorable conditions, may carry the diameter of the fully mature system to as much as 500 miles.

This term "the fully mature system," describes the end of the third phase of development, which may be designated the "*expanding*" phase. The expanding process normally continues much beyond the time when the deepening phase is finished. The very steep barometric gradient into the small, intense vortex of the young cyclone produces extremes of wind velocity that are seldom if ever found thereafter during the later history of the storm. Although atmospheric viscosity is small and the high symmetry of the vortical circulation minimizes its peripheral drag on surrounding, more quiescent air, there must be a definite tendency to draw in additional masses, that is, to increase the diameter of the system.

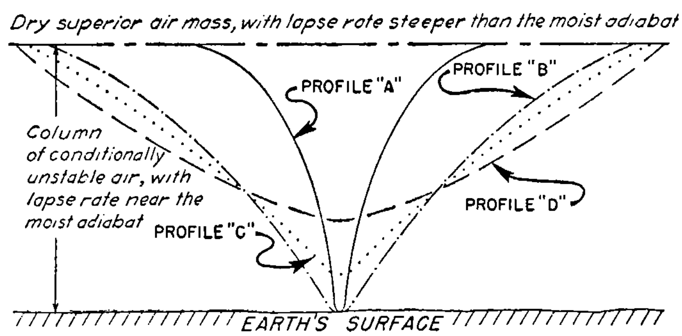

FIGURE 3.—Diagram illustrating vortical conditions (pressure profiles) representative of different stages in cycle of hurricane development and decay. Profile A, young vortex, at end of developing stage. B, fully mature, with gradient balanced by opposing influences. C and D, declining phases, with excess inflow of air, diminishing pressure gradient, and weakening vortex.

Giving a barometric minimum which has reached its limit of depth, with an attendant atmospheric vortex that continues to drag into its periphery, even at a slow rate, the air about it, the diameter of the vortex must increase while the steepness of barometric gradient into the center decreases. (Fig. 3.)

Internal and external resistances such as viscosity, friction with the earth's surface and internal and peripheral turbulence, are constantly drawing upon the energy of the vortical circulation; and these influences increase with the increasing diameter and area of the cyclone. The primary driving power of the system, which must be proportional to the difference between the central and peripheral pressures, cannot increase after the limiting depth of barometric minimum has been reached. Hence there must inevitably be a limit to the possibility of expansion in diameter, set in part at least by the same conditions that limited the deepening of the original vortex.

Latitude effects have been excluded from the reason-

[10] F. G. Tingley. The genesis of a tropical cyclone. MONTHLY WEATHER REVIEW vol. 39, pp. 340–347, 1911.

ing so far, and the discussion should be considered as applicable to a tropical cyclone moving along a parallel of latitude through a normal tropical marine environment. No mention has been made of the requirements or the mechanism for the continual supply of energy from inflowing warm moist air that is essential to sustain the normal development suggested; lack of a favorable environment would constitute one of the accidents that might distort the normal cycle at any point in its progress.

The effect, upon the circulation, of the increasing deflective influence that accompanies movement of a tropical cyclone to higher latitudes is, however, to be considered. This influence operates at all times toward an expansion of the diameter of the cyclone and it therefore belongs to the processes of the third phase; but it also continues to act in the last or *"declining"* phase. Deflection by the earth's rotation is a persistent influence working toward expansion of the area of a poleward-moving cyclonic system; and since many of the demands on storm energy come from resistances, as enumerated above, that depend directly upon area and circumference, the *"braking power"* of the deflective influence continues to operate beyond the time when a balance has been reached between energy supply, depth, and diameter attained by the cyclone at the end of the third, or *"expanding"* phase.

There seems to be no contraction process by which an overextended gradient can be restored to greater steepness by a shortening of cyclonic diameter. Cyclones are sometimes deepened and re-energized by a sort of refueling process whereby an air supply of higher energy content is made available; but it is the writer's opinion that in such cases the cyclone as a whole will be found to continue at its former size or actually to grow in extent.

The environment of tropical cyclones seldom provides such contrasting air masses as to afford much of this type of abnormal re-energizing. Hence, as the diameter of a tropical cyclone reaches the limit set by preexistent environmental factors, there can be but one further process of change, and the self-energizing ability of the system must diminish. The gradient will fail to maintain rotation at a rate that counteracts the tendency to an oversupply of inflowing air; the center begins to fill, and the barometric gradient thereafter suffers a rapid decrease; rotational velocities cannot be maintained and the whole system succumbs to friction and other disintegrating influences.

How often, if ever, tropical hurricanes actually complete, undisturbed, such a normal cycle of development and decline is impossible to estimate. Many, perhaps most of them, fail to do so. Distortion or interruption may occur at any stage whatever. If, however, there be this fairly regular progression of changes that characterizes the normal type, our recognition of this principle should enable us better to deal with the many abnormalities that undoubtedly occur and, furthermore, should aid us to anticipate what observational evidence to look for in order to locate hurricane disturbances at various stages of development.

For instance, there should be no expectation of finding exactly the same sort of sea disturbance in the vicinity of a small, very intense, young cyclone as will attend a mature hurricane of large diameter. In the earlier, more intense, phase the sea will of course be locally agitated with a violence greater than could be expected at the stage when the barometric gradient has become broader and less steep; but because the area of the young cyclone is small, the field of its influence shifts quickly to new and undisturbed sea areas, and the cumulative effects in the wave response (technically attributed to the "length of fetch" of the wind) are therefore of less importance than they are later when the area of the wind action is much larger.

It may, therefore, be anticipated that the swells from small, deep vortices will not differ much on opposite sides of the center of action. On the other hand, where large, mature storms are concerned, there would seem to be a much greater tendency for relatively long swells to run out ahead of the storm center. Such an expanded storm area, approaching over an open sea, can thus give the characteristic outrunning evidences in effects of swell and tide on shores in the line of its advance, as described by Cline,[11] but young (even though intense) storms, of small diameter, would show much less pronounced *advance* effects in swells and coastal tides, although the tidal effects may be very large as the center crosses a coastline.

Estimates of location and movement of tropical disturbances must oftentimes be based upon very meager observational material, not only as to the effects on the sea surface, but also as to meteorological observations. Where reports are few as is so often the case at sea, meteorologists inevitably show wide divergence of opinion in their interpretation of the inadequate evidence available. If it be accepted that characteristic differences distinguish phases in the cycle of hurricane development in some such manner as is herein suggested, there should at least be better agreement in such situations, and perhaps also practical benefits in hurricane forecasting.

To summarize, the writer's hypothesis attempts to bring into logical relation the general phenomena of tropical storms, as characterizing the process of a normal cycle of origin, development, and disintegration, recognizing four stages, as follows:

First.—The *"preliminary"* phase is represented as requiring a widespread condition of potential (convective) instability, in which vertical exchange is to a considerable degree suppressed by what is here called a "factor of kinetic stability," attributed to the action of the steady flow of the trade or monsoon wind stream; this condition occasionally breaks down to permit cyclogenesis by (*a*) distortion of the predominant wind stream (and its attendant barometric field) due to an advective "push" of a high-level air mass from a heated continental source, this distortion being attended by (*b*) increased convective overturning and concentration of heavy rainfall in the area subjected to greatest disturbance of the preexistent (balanced) wind stream. This action in turn permits the localization of vortical tendencies; and the further involvement of the central air column may finally extend to the level of any overlying advective air mass.

Second.—Once the whole air column is involved, the progressive localization and intensification of vortical action will proceed rapidly through the *"deepening"* phase, the limit to which is set by the thermodynamic characteristics of the environment; the young vortex expands at a relatively slow rate, and is usually at maximum intensity of gradient (and of wind velocity) at the end of the deepening phase.

Third.—The *"expanding"* phase is characterized by steady increase in the diameter of the cyclonic vortex through progressive involvement of peripheral air masses; but the pressure minimum remains about stationary, with a resultant lowering of the barometric gradient. Maturity with maximum development of total kinetic energy, is reached in this phase.

Fourth.—In the *"declining"* phase the processes of disintegration predominate because pressure gradient dimin-

[11] Cline, I. M. *Tropical Cyclones*, New York, 1926.

ishes beyond the point at which eviction of air equals or exceeds inflow to the vortex, an excess of air enters the system, the vortex fills and is destroyed.

The last three phases are to a considerable degree distinguishable only as separate maxima in effects of factors operating simultaneously throughout but at rates which distribute these maxima into different successive periods in a continuous process.

METEOROLOGICAL AND CLIMATOLOGICAL DATA FOR JANUARY 1942

[Climate and Crop Weather Division, J. B. KINCER in charge]

AEROLOGICAL OBSERVATIONS

TABLE 1.—*Mean free-air barometric pressure in millibars, temperature in degrees Centigrade, and relative humidities in percent, obtained by airplanes and radiosondes during January 1942*

Altitude (meters) m. s. l.	Stations with elevations in meters above sea level																											
	Albuquerque, N. Mex. (1620 m.)				Atlanta, Ga. (300 m.)				Bismarck, N. Dak. (505 m.)				Boise, Idaho (864 m.)				Brownsville, Tex. (6 m.)				Buffalo, N. Y. (221 m.)				Charleston, S. C. (14 m.)			
	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity
Surface	31	841	3.1	42	31	985	3.8	71	31	958	−8.4	77	31	925	−5.8	89	31	1,022	12.5	88	30	989	−4.3	77	31	1,019	6.7	81
500					31	962	5.7	63									31	964	13.5	75	30	955	−5.0	83	31	960	8.5	66
1,000					31	905	4.6	59	31	900	−4.6	74	31	909	−4.2	87	31	908	11.7	70	30	896	−7.0	81	31	904	6.5	61
1,500					31	851	3.9	52	31	844	−5.5	69	31	854	−3.7	85	31	856	9.9	65	30	840	−8.4	77	31	851	4.8	55
2,000	31	803	3.4	42	31	800	3.1	44	31	791	−6.4	64	31	801	−2.5	79	31	805	8.7	57	30	787	−9.5	71	31	800	3.7	49
2,500	31	754	0.7	43	31	752	1.7	39	31	742	−8.6	62	31	752	−3.3	73	31	758	7.3	48	30	738	−11.1	68	31	752	1.7	42
3,000	31	709	−1.8	43	31	706	−0.6	36	31	695	−11.0	60	31	706	−5.1	70	31	713	5.6	43	30	691	−12.9	66	31	706	−0.6	38
4,000	31	624	−7.2	40	31	622	−6.6	35	31	610	−16.9	58	30	621	−10.3	64	31	630	−0.2	36	30	605	−18.1	63	31	622	−6.1	36
5,000	31	548	−12.8	38	31	547	−13.0	35	30	533	−23.3	57	30	544	−17.0	61	31	556	−6.5	33	30	528	−24.3	61	30	547	−12.9	36
6,000	31	480	−19.3	37	31	479	−19.6	35	29	464	−30.1	56	30	476	−23.6	57	30	488	−13.7	32	30	460	−31.3	60	28	479	−19.9	36
7,000	31	419	−26.5	36	31	418	−26.7	34	29	402	−37.2	55	30	414	−30.3	57	30	427	−21.0	32	30	398	−38.0	58	28	418	−26.9	35
8,000	31	364	−33.8	35	30	363	−34.1	33	29	347	−43.9		28	359	−37.4	57	28	373	−28.1	32	30	344	−44.5		26	363	−34.0	36
9,000	31	315	−41.0		30	314	−41.2		29	298	−49.6		27	310	−44.8		27	323	−35.3	33	29	295	−50.0		26	314	−40.9	
10,000	30	272	−47.7		29	270	−47.8		29	256	−54.5		25	266	−51.6		27	280	−42.2		25	254	−54.0		26	270	−47.6	
11,000	29	233	−53.5		29	232	−52.2		28	219	−56.9		24	228	−56.6		25	240	−49.7		25	217	−55.4		26	232	−52.4	
12,000	29	199	−55.4		29	199	−54.7		24	186	−57.7		22	194	−58.5		23	206	−55.3		23	185	−54.0		23	199	−55.7	
13,000	29	170	−56.0		28	170	−56.1		22	159	−56.8		18	166	−56.0		23	175	−61.0		22	158	−54.2		20	170	−57.2	
14,000	28	145	−57.5		28	145	−57.5		18	135	−56.2		18	141	−55.1		22	149	−66.6		19	135	−55.0		19	144	−60.3	
15,000	27	124	−59.5		25	124	−60.3		16	115	−57.4		16	120	−56.6		18	126	−71.7		18	116	−55.5		18	123	−63.2	
16,000	25	106	−62.3		18	105	−63.0		13	98	−59.2		15	103	−58.2		15	107	−76.8		16	98	−56.3		16	104	−65.4	
17,000	22	90	−63.8		11	89	−65.7		8	83	−59.7		14	88	−58.8		9	89	−79.4		7	84	−56.8		7	89	−67.2	
18,000	15	76	−64.0														6	75	−80.1									

Altitude (meters) m. s. l.	Denver, Colo. (1,616 m.)				Detroit, Mich. (194 m.)				El Paso, Tex. (1,193 m.)				Ely, Nev. (1,908 m.)				Great Falls, Mont. (1,128 m.)				Huntington, W. Va. (172 m.)				Joliet, Ill. (178 m.)			
	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity	Number of observations	Pressure	Temperature	Relative humidity
Surface	31	840	−4.9	72	31	993	−4.9	84	31	886	6.5	50	31	812	−5.7	84	30	890	−1.4	61	31	999	−1.5	77	29	996	−6.0	86
500					31	954	−5.3	83													31	959	−0.7	74	29	957	−5.9	85
1,000					31	896	−6.5	77													31	900	−2.8	72	29	897	−6.4	78
1,500					31	840	−6.7	69	31	854	8.8	47					30	849	0.1	57	31	845	−4.6	69	29	842	−6.4	71
2,000	31	800	−0.5	58	31	788	−7.7	63	31	803	6.3	46	31	803	−3.3	80	30	797	−2.7	54	31	792	−5.5	61	28	789	−7.4	67
2,500	31	751	−2.0	54	31	738	−9.5	63	31	756	4.0	45	31	754	−2.9	72	30	748	−5.5	53	31	744	−7.4	57	28	740	−9.1	65
3,000	31	706	−4.8	51	31	692	−11.8	62	31	710	1.7	42	31	708	−4.5	64	30	701	−8.5	52	31	697	−9.3	55	28	693	−11.4	62
4,000	31	620	−11.3	49	31	606	−17.0	62	31	627	−4.0	38	31	623	−9.7	61	30	616	−13.9	50	31	612	−14.5	54	28	607	−16.8	59
5,000	31	544	−17.8	48	31	530	−23.0	61	31	551	−10.5	36	31	546	−15.3	57	30	539	−20.8	48	31	536	−20.0	53	28	531	−22.8	61
6,000	31	475	−25.0	46	29	462	−29.4	56	30	483	−17.3	36	30	478	−21.9	56	29	470	−28.0	48	30	468	−26.5	53	28	462	−29.6	60
7,000	31	413	−32.0	45	28	400	−35.9	54	29	422	−24.4	35	29	416	−29.4	53	29	408	−35.3	47	28	406	−33.6	52	28	401	−36.6	58
8,000	31	357	−39.2	42	27	346	−42.6		29	367	−32.0	35	28	361	−36.9	52	29	353	−42.2		26	351	−41.2		28	346	−42.8	
9,000	31	308	−46.2		26	298	−48.9		29	318	−39.8	35	27	312	−44.8		29	303	−48.9		24	302	−48.5		28	298	−48.2	
10,000	30	265	−51.9		24	255	−52.2		28	274	−47.4		25	268	−52.1		28	260	−55.1		22	259	−53.3		27	255	−52.2	
11,000	30	227	−55.6		21	219	−54.2		28	235	−54.0		25	229	−57.5		28	223	−59.1		20	222	−55.5		27	219	−54.2	
12,000	30	194	−55.9		17	187	−53.3		28	201	−57.3		25	196	−58.6		28	190	−60.0		18	189	−55.9		27	187	−54.0	
13,000	27	165	−55.5		15	160	−52.5		28	171	−58.7		21	167	−57.9		26	161	−58.0		14	160	−56.3		25	160	−53.4	
14,000	26	141	−56.6		12	137	−51.5		26	146	−61.6		17	142	−58.8		23	138	−57.9		12	136	−57.9		24	137	−54.4	
15,000	24	120	−58.7		10	117	−53.1		24	124	−64.4		12	122	−61.0		20	118	−59.6		7	116	−60.0		18	117	−55.7	
16,000	21	102	−60.8		8	100	−54.4		24	105	−68.3		7	104	−63.8		13	100	−60.7						13	99	−57.4	
17,000	14	87	−61.6						17	89	−71.1						5	85	−60.8						8	84	−58.5	
18,000	6	74	−61.6						11	75	−71.2																	